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Vailulu'u undersea volcano: The New Samoa

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[1] **Abstract:** Vailulu'u Seamount is identified as an active volcano marking the current location of the Samoan hotspot. This seamount is located 45 km east of Ta'u Island, Samoa, at 169°03.5′W, 14°12.9′S. Vailulu'u defines the easternmost edge of the Samoan Swell, rising from the 5000-m ocean floor to a summit depth of 590 m and marked by a 400-m-deep and 2-km-wide summit crater. Its broad western rift and stellate morphology brand it as a juvenile progeny of Ta'u. Seven dredges, ranging from the summit to the SE Rift zone at 4200 m, recovered only alkali basalts and picrites. Isotopically, the volcano is strongly EM2 in character and clearly of Samoan pedigree ($^{87}Sr/^{86}Sr$: 0.7052–0.7067; $^{143}Nd/^{144}Nd$: 0.51267–0.51277; $^{206}Pb/^{204}Pb$: 19.19–19.40). The ^{210}Po-^{210}Pb data on two summit basalts indicate ages younger than 50 years; all of the recovered rocks are extremely fresh and veneered with glass. An earthquake swarm in early 1995 may attest to a recent eruption cycle. A detailed

nephelometry survey of the water column shows clear evidence for hydrothermal plume activity in the summit crater. The water inside the crater is very turbid (nephelometric turbidity unit (NTU) values up to 1.4), and a halo of "smog" several hundred meters thick encircles and extends away from the summit for at least 7 km. The turbid waters are highly enriched in manganese (up to 7.3 nmol/kg), providing further evidence of hydrothermal activity. Vailulu'u is similar to Loihi (Hawaii) in being an active volcanic construct at the eastern end of a hotspot chain; it differs importantly from the Hawaiian model in its total lack of tholeiitic basalt compositions.

Keywords: Samoa; volcano; Vailulu'u; hydrothermal; nephelometry; isotopes.

Index terms: Volcanology; hydrothermal systems; isotopic composition/chemistry; igneous petrology.

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1. Introduction

[2] Submarine volcanism and its associated hydrothermal systems are among the most vivid illustrations of the dynamic nature of the physical, chemical, and biological systems of planet Earth. Studies of these features have contributed fundamentally to our understanding of how the Earth works. These phenomena help us understand how the Earth loses its heat [*Wolery and Sleep*, 1976] and how processes of the solid Earth interact with processes in the hydrosphere and biosphere. The geochemistry of intraplate oceanic hotspot volcanoes has revealed much detail about how the Earth's crust-mantle system has evolved through Earth history [*Zindler and Hart*, 1986]. Submarine hydrothermal systems have received much attention because of their impact on the geochemical cycles of many elements and the character and evolution of their biological habitats.

[3] Most of our knowledge of submarine volcanic-hydrothermal systems is based on studies from active spreading ridges. These studies have shown that chemical fluxes and the transport of heat can vary substantially between different systems, complicating the construction of generalized thermal or chemical budgets. Only one active intraplate submarine volcanic system has been studied in reasonable detail: Loihi, in the Hawaiian chain [*Fornari et al.*, 1988; *Duennebier and the 1996 Loihi Science Team*, 1997; *Davis and Clague*, 1998]. A few others have received cursory study: Macdonald [*Stoffers et al.*, 1989; *Cheminée et al.*, 1991]; Teahitia [*Cheminée et al.*, 1989; *Michard et al.*, 1993]; Boomerang [*Johnson et al.*, 2000]. In addition to the paucity of attention given to intraplate submarine hydrothermal systems, our understanding of hotspot volcanism itself is dominated by concepts that have developed over many decades of study of the Hawaiian archipelago and its submarine slopes [e.g., *Clague and Dalrymple*, 1989]. This has led to a standard model for the evolution of oceanic volcanoes that is strongly rooted in observations from Hawaii.

[4] In this letter, we report on the mapping and investigation of Vailulu'u seamount, a new and

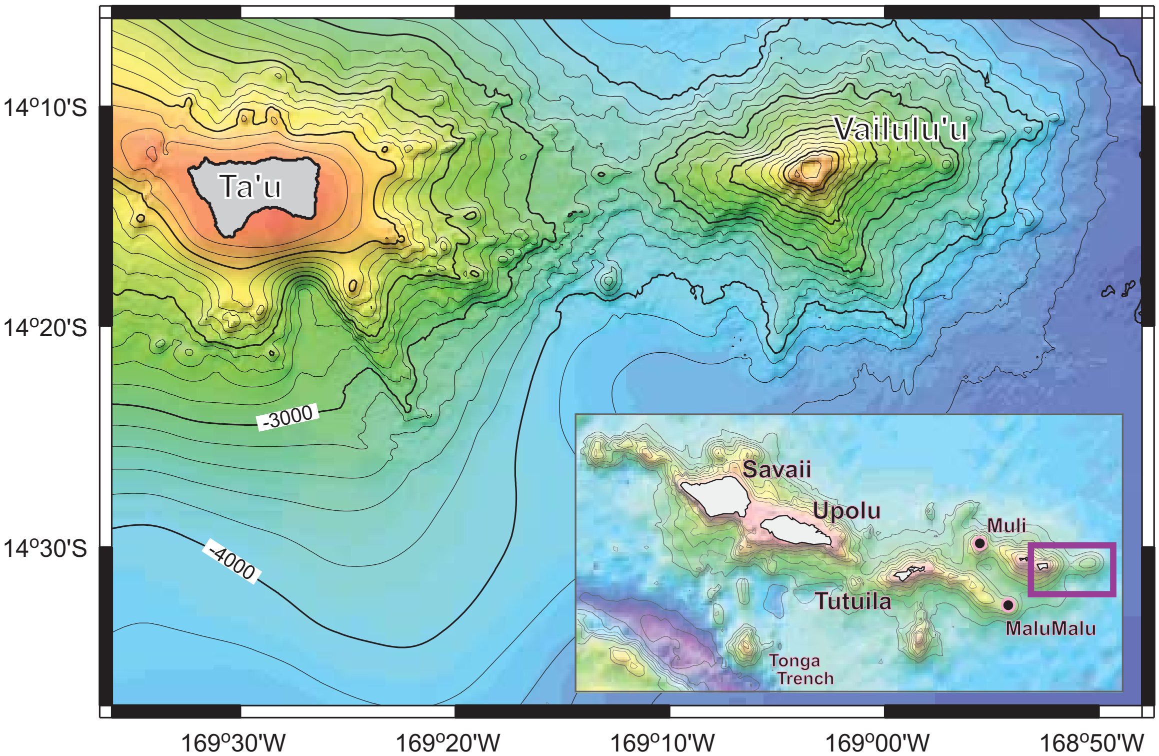


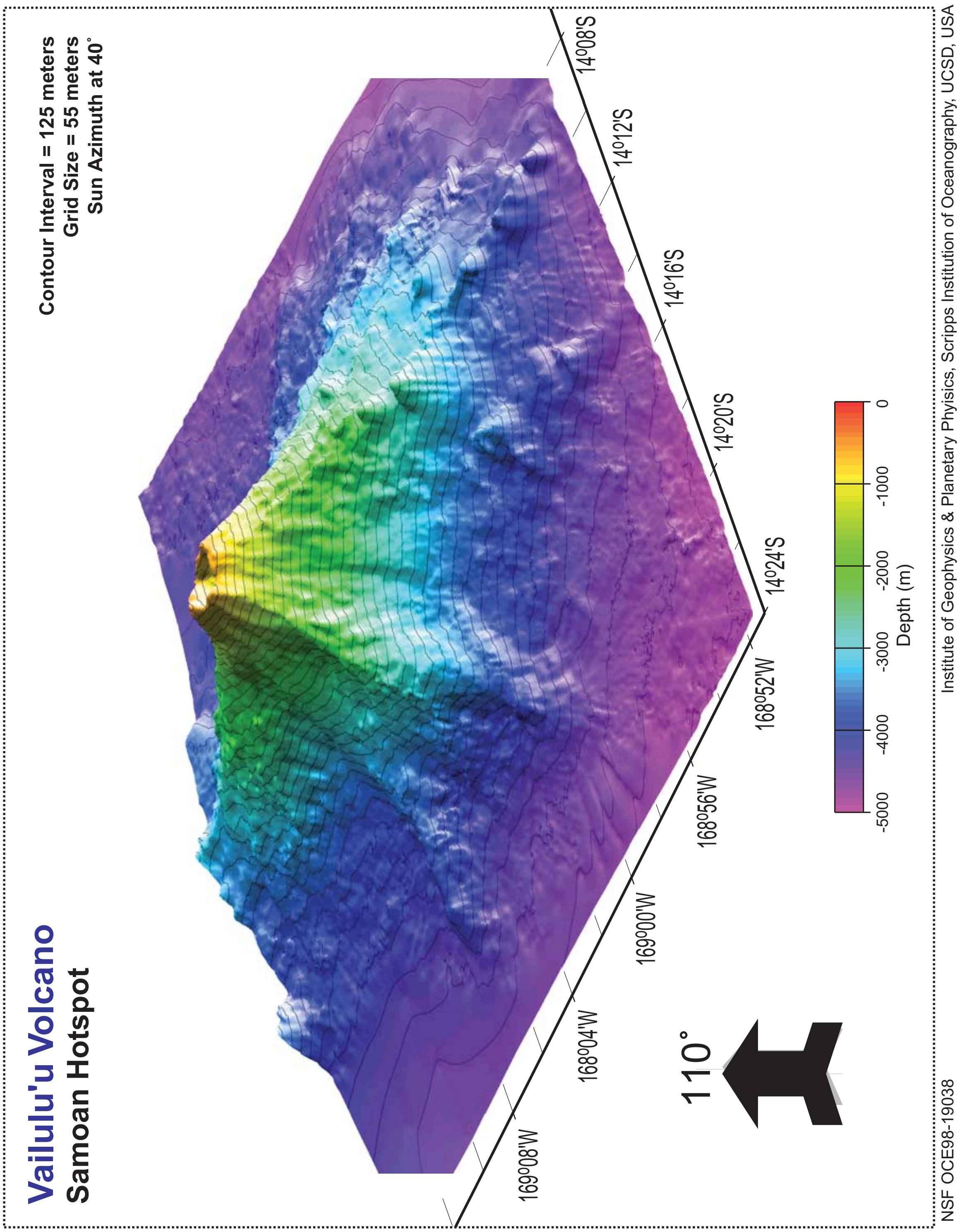
Figure 1. Bathymetry of Vailulu'u and nearby Ta'u Island, based on a SeaBeam bathymetric survey performed during R/V *Melville*'s AVON 2 and 3 cruises, augmented with satellite-derived bathymetry from *Smith and Sandwell* [1996]. The inset shows the general location of Vailulu'u with respect to the Samoan Archipelago; two other newly mapped and dredged seamounts (Malumalu and Muli, AVON 3 cruise) are shown as well. Vailulu'u displays an overall asymmetric star-like pattern of rift zones and ridges, with a geometry that would closely resemble the shape of Ta'u Island in its more juvenile days.

particularly interesting active submarine volcano. We show that Vailulu'u is of Samoan lineage and represents the current location of the Samoan hotspot. Vailulu'u is an important example for study, both because it is an active and "typical" oceanic intraplate volcano and because it offers unique features that other submarine volcanoes do not. Its shallow depth provides easy access, its simple morphology and enclosed crater will allow estimation of hydrothermal fluxes, and its geochemical pedigree as a Samoan volcano gives it a highly characteristic mantle source signature. We present data here that document these aspects of Vailulu'u and its potential to substantially revise our views on ocean intraplate volcanism and to further our understanding of submarine hydrothermal systems in general. Vailulu'u offers a valuable counterpoint to Loihi and to the standard hotspot model commonly exemplified by Hawaii.

2. Structure and Morphology

[5] Vailulu'u Seamount[1] was discovered on October 18, 1975, by Rockne Johnson [*John-*

[1] Vailulu'u Seamount was named in April 2000 by Samoan high school students; the name refers to the sacred sprinkling of rain that reportedly always fell as a blessing before a gathering of King Tuimanu'a, the last king of the Samoan Nation. Previous, informal names include Rockne Volcano [*Johnson*, 1984] and Fa'afafine seamount [*Hart et al.*, 1999].


Vailulu'u Volcano
Samoan Hotspot
Contour Interval = 125 meters
Grid Size = 55 meters
Sun Azimuth at 40°
110°
169°08'W
168°04'W
169°00'W
168°56'W
168°52'W
14°08'S
14°12'S
14°16'S
14°20'S
14°24'S
Depth (m)
0
-1000
-2000
-3000
-4000
-5000
NSF OCE98-19038
Institute of Geophysics & Planetary Physics, Scripps Institution of Oceanography, UCSD, USA

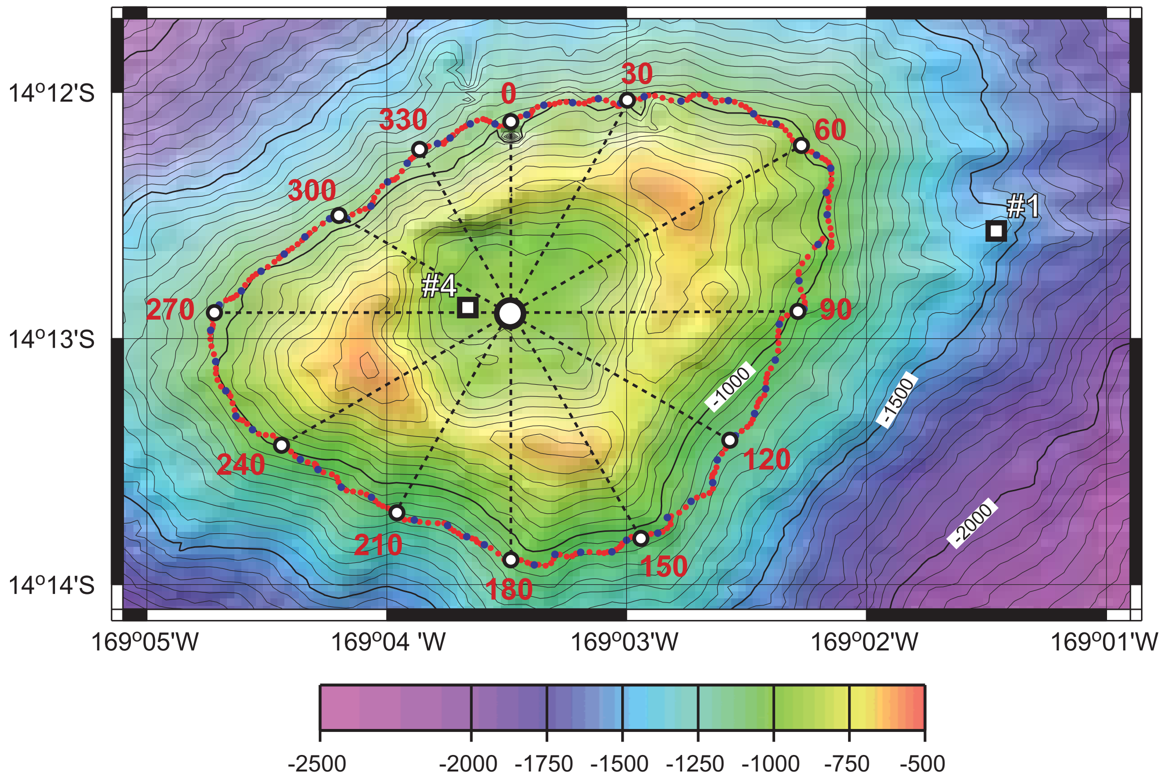


Figure 3. SeaBeam bathymetry map of the summit crater of Vailulu'u, showing the crater rim with three peaks and three breaches, the location of CTDO casts 1 and 4, and the tow-yo track circumnavigated around the summit. Dotted azimuth lines are given every 30° along the track, to correspond with the nephelometry contour section shown in Figure 6.

son, 1984] from the ketch *Kawamee* and mapped in March 1999 with SeaBeam aboard the R/V *Melville* during AVON cruises 2 and 3 (Figures 1 and 2). These cruises were motivated by seismic events in this region that occurred in 1973 and 1995, respectively. The AVON cruises were a direct attempt to find the current location of the Samoan hotspot. *Johnson* [1984] accurately defined Vailulu'u's location and summit height, but his discovery remained virtually unknown because he was unable to identify this feature as an active volcano.

[6] Vailulu'u seamount is located at 169° 03.5′W, 14°12.9′S, 45 km east of Ta'u island, the easternmost island of the Samoan chain, and defines the leading edge of the Samoan swell at 5000-m water depth (Figure 1). Vailulu'u rises from an ocean depth of 4800 m to its crater-rim within 590 m of the sea surface, with a total volume of ~1050 km^3. Vailulu'u's summit includes a 400-m-deep and 2-km-wide crater (Figure 3). The current dimensions of the volcano are consistent with Johnson's original 600-m summit depth [*Johnson*, 1984], indicat-

Figure 2. Perspective view of Vailulu'u seamount looking NW, displaying three major rifts toward the east, southeast, and west. The lower slopes of Vailulu'u and Ta'u merge along the west ridge, with a saddle at 3200 m. Vailulu'u is ~35 km in diameter at its base.

ing that no major net volcanic growth or collapse has occurred over the last 25 years.

[7] The overall shape of Vailulu'u is dominated by two rift zones extending east and west from the summit, defining a lineament that is parallel to the Samoan hotspot track. This is similar to the dominant trends defined by isolated (non-buttressing) Hawaiian volcanoes that have been explained by crustal extension at the crest of the swell [*Fiske and Jackson*, 1972]. A third, slightly less well developed rift extends SE from the summit, and several minor ridges extend out from the lower slopes of Vailulu'u, giving it an overall asymmetric, star-like pattern. Rift zones and ridges in the southern sector are more strongly developed than those on the northern flank, giving Vailulu'u a stunning similarity to a "Young Ta'u" island (Figure 1). The three major rift zones define three high points of the crater rim and thus are likely to be part of the present-day plumbing system of the volcano. Ridges emerging from the lower flanks may be related to earlier constructive events in the history of the volcano or may be landslide deposits (Figures 1 and 2). In addition to the constructive nature of the major rifts, Vailulu'u shows clear signs of slope collapse and mass wasting. Such features are prominently displayed at the emergence point of the western rift, where it narrows owing to the amphitheater-shaped scars on both the north and south sides of its upper slopes. Steep, concave contours of the upper slopes merge into convex contours farther downslope, defining sedimentary aprons (Figures 1 and 2). Similar structures are common on other seamounts [*Vogt and Smoot*, 1984]; on Vlinder Seamount these have been related to intrusive oversteepening of the upper rift zone slopes [*Koppers et al.*, 1998].

[8] The crater and rim of Vailulu'u are oval-shaped, with two well-developed pit craters defining the northern two thirds of the crater and two minor depressions present on a bench in the southern third of the crater (Figure 3). The crater wall has a "scalloped" appearance that suggests mass wasting during multiple crater-collapse events.

[9] A significant number of dredge samples have been characterized with respect to major and trace elements, radiogenic isotopes, and volatile abundances. Analyses of 41 glass samples from 7 dredges show that the summit and deeper east and SE rifts are relatively homogeneous alkali basalts (SiO_2 = 46–48%, Na_2O + K_2O = 3.5–4.9%, MgO = 5–9%). Vailulu'u does not show the extreme compositional variability of its Hawaiian counterpart, Loihi Seamount, which ranges from tholeiite to basanite. The shield and posterosional stages of Samoan subaerial volcanism are also firmly alkalic, again unlike the Hawaiian case.

[10] The major element compositional homogeneity of Vailulu'u lavas contrasts with its variability in some radiogenic isotope ratios, in particular, $^{87}Sr/^{86}Sr$ that varies between 0.7052–0.7067 (Figure 4). In addition to these heterogeneitites in source region composition, Vailulu'u glasses display significant variation in volatile contents, largely indicating differences in outgassing behavior. Summit lavas tend to be more outgassed in H_2O than lower rift zone lavas. Summit samples typically have H_2O/K_2O ratios less than 1, while the deep rift dredges (>3800 m) show ratios from 1 to 1.5. H_2O/Cl ratios are also different between shallow and deep dredges (5–9 versus 7–20, respectively). There is no indication in the Cl data for involvement of seawater [*Michael and Cornell*, 1998] in the magmatic plumbing system.

3. Temporal Aspects of Vailulu'u Volcanism

[11] Several historical events suggest volcanic activity at Vailulu'u volcano. There was a series of sound fixing and ranging (SOFAR)-recorded

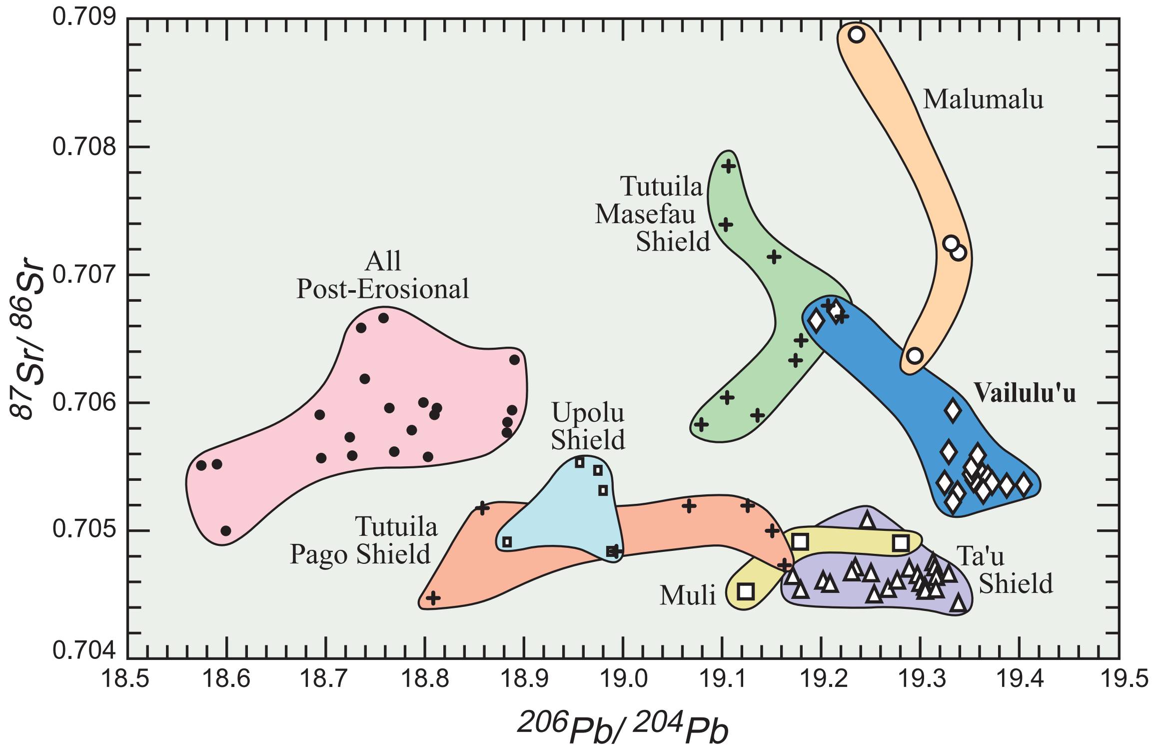


Figure 4. Sr-Pb isotope plot for basalts from Vailulu'u volcano, in comparison with data from Muli and Malumalu seamounts and the subaerial Samoan islands of Ta'u, Tutuila, Upolu, and Savai'i; see Figure 1 for locations. The posterosional field includes basalts from Savai'i, Upolu, and Tutuila (data are from *Wright and White*, 1987; *Farley et al.*, 1992; *Hauri and Hart*, 1993; *Hart et al.*, 1999; S. R. Hart et al., unpublished data, 2000).

explosions on July 10, 1973, and during the period January 9–29, 1995, the global seismic network recorded a strong (*M*4.2–4.9) earthquake swarm in the vicinity of Vailulu'u. While most of the 1995 earthquakes were formally located NW of the volcano, their uncertainty ellipses include Vailulu'u; a SeaBeam survey carried out within the earthquake area did not reveal any volcano tectonic features.

[12] Dredges, especially those from the summit area, are dominated by extremely fresh volcanic rock, with pristine volcanic glass, many original glassy surfaces, unaltered olivine phenocrysts, and a virtual lack of vesicle fillings. Furthermore, the intensities of SeaBeam sidescan returns are extremely "bright," suggesting that fresh volcanic rocks occur ubiquitously throughout the slopes of Vailulu'u and that sediment cover is largely absent.

[13] Two basalt samples were analyzed for complete U-series nuclides, one from the floor of the crater and one from the outer NE slope of the summit cone (^{210}Po and ^{210}Pb by counting [*Fleer and Bacon*, 1984], ^{226}Ra and ^{230}Th by mass spectrometry [*Sims et al.*, 1999]). The crater floor sample shows $^{210}Po/^{210}Pb$ equilibrium but $^{210}Pb/^{226}Ra$ disequilibria (activity ratio of 1.71). This suggests an eruption age of less than 30–50 years. The other sample shows both $^{210}Po/^{210}Pb$ and $^{210}Pb/^{226}Ra$ disequilibria (1.12 and 1.20, respectively), confirming an "age" of less than 5–10 years. Note

that the excess of ^{210}Po found here is different from the normal situation, where ^{210}Po is degassed during eruption [*Rubin et al.*, 1994].

4. Pedigree of Vailulu'u Volcano

[14] On the basis of its morphological connection to Ta'u Island via its west rift zone (Figure 1) and its expression as the easternmost volcanic construct along the Samoan chain, it is natural to view Vailulu'u as a young volcano of Samoan lineage. Proof of this comes from isotopic fingerprinting of 18 basalt samples from various locations on the volcano. The ^{87}Sr/^{86}Sr–^{206}Pb/^{204}Pb isotope data for these samples is shown in Figure 4, in comparison with data from other Samoan localities. Vailulu'u shows a strong enriched mantle 2 (EM2) mantle signature, which is the hallmark of Samoan volcanism. While Vailulu'u partly overlaps the existing Samoan field, it also extends to higher ^{206}Pb/^{204}Pb than other Samoan basalts, continuing a west-to-east trend of increasing ^{206}Pb/^{204}Pb in Samoan shield lavas. Helium isotope data on samples from five dredges range from 7.8 to 10.4 Ra and barely overlap the known range from subaerial Samoa (10–26 Ra [*Farley and Neroda*, 1998]). There is some indication that ^{3}He/^{4}He in the Samoan plume peaked at 26 Ra during passage under Tutuila and that it has been decreasing since (subaerial and dredge samples from Ta'u range in He from 13 to 19 Ra [*Farley and Neroda*, 1998; S. R. Hart et al., unpublished data, 2000]).

5. Water Column Characteristics Over Vailulu'u Volcano

[15] During the DeepFreeze 2000 cruise in March 2000, aboard the U.S. Coast Guard Icebreaker *Polar Star*, conductivity temperature depth optical (CTDO)/Niskin stations were occupied at three places within the summit crater and two outside the crater; in addition, the summit area was circumnavigated in tow-yo mode [*Baker and Massoth*, 1987] along an ~1000-m contour (Figure 3). We studied particulate distribution in the water column using a light backscattering sensor (LBSS) attached to a CTD/Niskin water sampling rosette. The LBSS profile for station 4, inside the crater, is compared to data for station 1, outside the crater, in Figure 5. NTU values are essentially at background between 200 and 600 m at both stations. At 600-m depth in the crater profile the NTU values increase sharply and in a stepwise fashion, all the way to the bottom of the crater at 996 m. The NTU values near the bottom are very high, with values greater than 1.4; these are well above values associated with active venting and plume formation on ridge crests [*Resing et al.*, 1999; *Baker et al.*, 1995, 2000; *Chin et al.*, 1998]. At station 1, outside the crater, the LBSS "smog" layer starts at about the same depth (610 m) but returns to background values at a depth of 850 m. This depth interval is comparable to the range of elevations shown by the rim of the summit crater, which has peaks at 590 m, and a deepest breach at ~780 m (Figure 3). At station 5, 7.5 km east of the crater rim, a small NTU anomaly is still observable, with a value of 0.08 at a depth of 600–720 m.

[16] There are high Mn concentrations associated with these particulate anomalies, as shown in Figure 5. Background Mn in deep water outside the crater ranges from 0.002 to 0.003 ppb; inside the crater, in the deepest part of the NTU smog layer, the Mn ranges up to peak values of 0.4 ppb (7.3 nmol/kg). There is a good correlation between the NTU values and the Mn concentrations, with an overall ppb Mn/NTU ratio of ~0.5; this is significantly lower than that observed in plumes on most ridges (where ratios of 10–80 are reported [*Mottl et al.*, 1995; *Chin et al.*, 1998; *Resing et al.*, 1999]). The low ratio at Vailulu'u is due both to the much higher NTU values, and the sig-

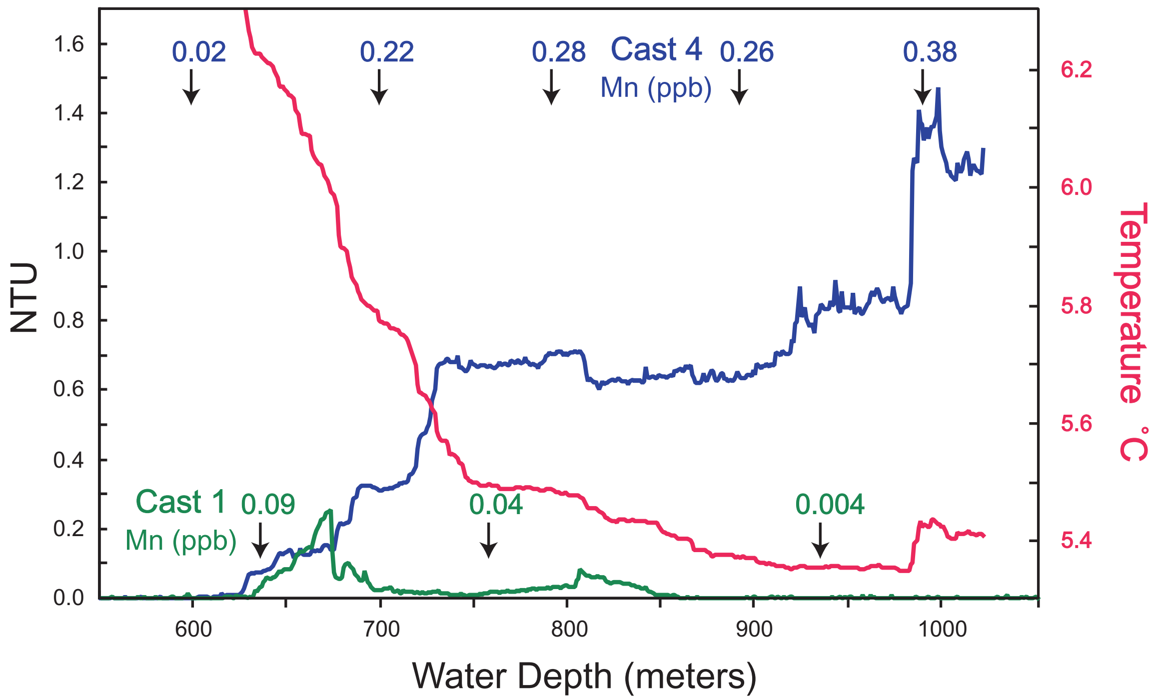


Figure 5. Temperature (red line) and light backscattering profiles for station 1 (green line), 1.2 km east of the crater rim, and station 4 (blue line), NW basin of the summit crater (see Figure 3 for locations). The nephelometry was done with a WET Labs light backscattering sensor (LBSS); data are calibrated using standard particulate suspensions [*Baker et al.*, 2000] and is reported as nephelometric turbidity units (NTUs). The conductivity cell on the CTD worked only intermittently; thus no potential density data are available for these profiles. The Mn data (numbers with arrows) are reported in ppb at discrete depths, next to the LBSS profiles (note that 1 ppb Mn = 18.2 nmol/kg). Ambient Mn levels in the water column are in the range 0.002–0.004 ppb. Mn analyses were performed on-shore on acidified and 0.4-μm filtered water samples, using an inductively coupled plasma-mass spectrometer procedure modified from *Field et al.* [1999].

nificantly lower Mn values (maximum Mn concentrations in ridge crest plumes are commonly in the 2–15 ppb range [*Field and Sherrell*, 2000; *James and Elderfield*, 1996; *Mottl et al.*, 1995; *Resing et al.*, 1999; *Baker et al.*, 1993, 1995].

[17] During a complete 360° circumnavigation of the summit crater, we mapped the plume between 500- and 900-m depth in tow-yo mode. The track of this survey is shown in map view in Figure 3; Figure 6 provides a 360° panoramic view of the plume "looking out" from a central location in the crater, contoured in NTU values. A projection of the elevation of the crater rim is also shown in Figure 6, providing an azimuthal view of its three major peaks and breaches. Overall, the hydrothermal plume (as visualized by NTU values) is confined to a narrow depth interval bracketed between the breaches and summits of the crater wall (Figure 6). Its upper, neutral buoyancy, level corresponds closely with the heights of the peaks on the crater rim. Virtually no particulate matter appears to be ejected from the crater to heights above the peaks on the crater rim nor does any settle below the breach depth, during its dispersion laterally away from the summit. Particulates are being generated within the crater and are subsequently carried away

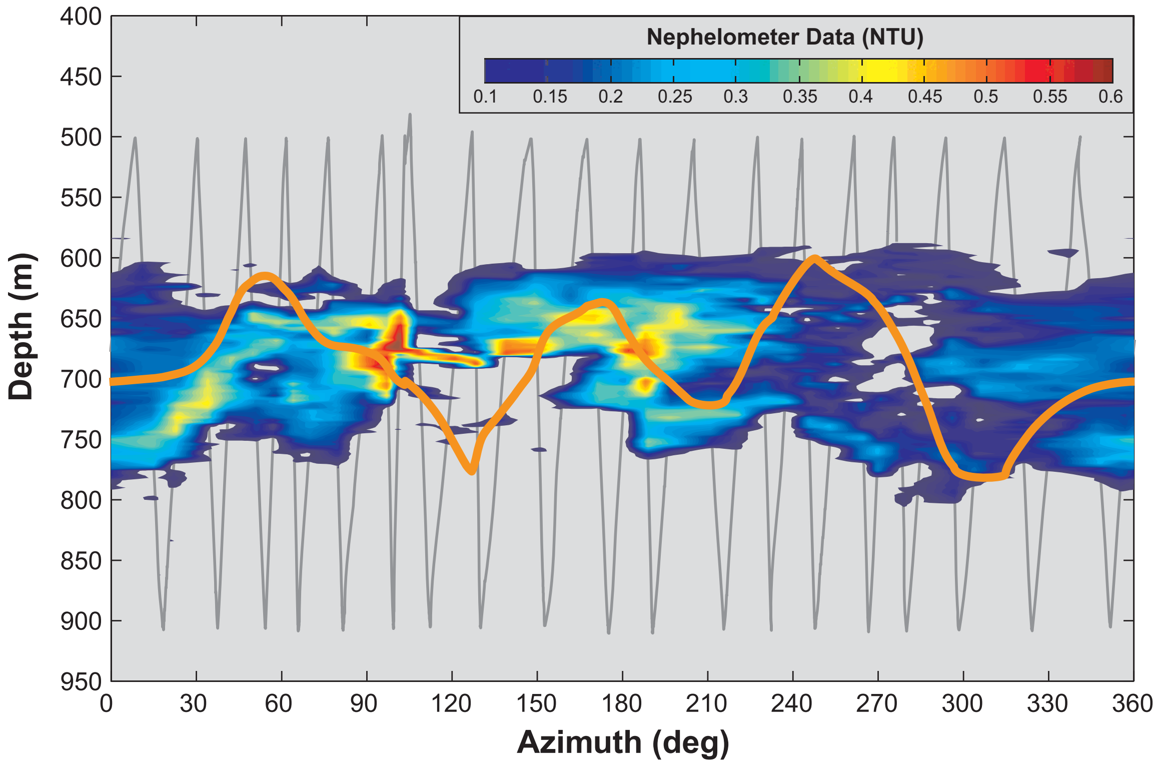


Figure 6. Nephelometry data for the CTDO tow-yo circumnavigation of the summit (track shown in Figure 3), contoured in NTU values and displayed as an "unwrapped" azimuth versus depth section, annotated in azimuth relative to the center of the volcano (north = 0°, east = 90°, etc.). The projection of the height of the rim of the summit crater is shown as a heavy orange line; the CTDO tow-yo track is shown in gray.

from the crater region by ocean currents. The presence of a plume in all directions around the crater suggests that these currents cannot be simple and unidirectional. However, a dominating current is indicated by the distribution of particulate intensities within the plume. The highest readings (NTU >0.5) are found in the angular segment between 90° and 200° and the lowest readings (NTU < 0.3) are found in the angular segment between 230° and 360°. These two segments are in opposite quadrants, suggesting a dominant current from ~280° (WNW). The 90°–200° segment also displays the most extreme gradients in NTU values, indicating that this plume region is least homogenized and most directly derived from the source of the particulate matter.

[18] While the upper limit of the plume appears to be at a rather constant depth of ~600–630 m, the lower limit shows very substantial azimuthal variability, ranging between 690 and 800 m. "Upwind" (NW), the plume fills the complete depth range, from highest summit elevation to deepest breach. "Downwind", however, the anomaly reaches only halfway down to the maximum depth of the breaches and displays relatively clear water in the lower half of the SE breach. This poses the problem that the lower half of the downwind breach appears to be venting clear water, despite the fact that no clear water was found in the crater and massive amounts of particulates are being vented to the SE. This situation may arise by upwelling of deep outside water in a downwind

"eddy," possibly even spilling deep ambient water into the crater through the lower half of the 130° breach.

6. Illations and Implications

[19] Vailulu'u volcano is clearly a young and currently active submarine volcano. Its activity is reflected in seismic events in 1973 and 1995, the lack of any sediment cover on the seamount, fresh basalt and pristine glass in dredges from all levels of the volcano, and radiometric ages ranging from 5 to 50 years. The summit is marked by a sharply delineated crater over 400 m deep, filled with highly turbid water with Mn concentration anomalies that are several orders of magnitude above ambient levels. This smog layer extends out as a halo for many kilometers in all directions, in a narrow depth interval defined by the range in depths of the rim of the summit crater. Hydrothermal activity in such a well-defined venting geometry provides a natural laboratory for a variety of quantitative tracer studies aimed at delineating the circulation of seawater through the seamount hydrothermal system, in the water column near the seamount and in the surrounding ocean basins.

[20] The "standard" model for hotspot or plume volcanism posits the youngest volcanism at the east end of Pacific volcanic island chains. The Samoan chain, with Vailulu'u at the east end, meets this test. Furthermore, the erosional maturity of Samoan volcanoes increases to the west; Ta'u is in undissected shield-building stage, Tutuila and Upolu are dissected and partly covered with rejuvenated flows, and Savai'i has virtually no subaerially exposed shield-stage lavas. This progression is similar to Hawaii, where Loihi is the easternmost volcano and where young rejuvenated lavas are present many hundreds of kilometers west of the current hotspot location (Oahu and Savai'i are 400 km from Loihi and Vailulu'u respectively). Unlike the Hawaiian chain, however, which is the archetype for the standard hotspot model, Vailulu'u is composed solely of alkali basalt, displays limited petrological diversity, and no tholeiite is in evidence. Vailulu'u does not merely represent the earliest "Loihi" stage of alkalic volcanism either, since the Ta'u Island shield is also composed solely of alkali basalts; tholeiites do occur on Tutuila and Upolu but are not abundant. In fact, tholeiites are uncommon in the active submarine and shield volcanism of many intraplate hotspot chains (Macdonald–Austral chain; Teahitia–Society chain; Adams and Bounty–Pitcairn chain). Thus Vailulu'u-Samoa may be a more appropriate "standard model" for ocean island volcanism than Loihi–Hawaii. It is likely that the physical processes involved in melt generation and melt modification are related to the total plume fluxes or mantle heat available. In this respect, the Samoan chain is much closer to a typical hotspot than Hawaii.

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